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AN ANALYSIS OF EARTHQUAKE FREQUENCY DATA

by

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AN ANALYSIS OF EARTHQUAKE FREQUENCY DATA

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ABSTRACT

Analyses of the times of occurrence of the major earthquakes recorded in periods of several years duration are presented for two regions along the San Andreas Fault in Central California. Components of tidal force and jerk are computed for each earthquake in the sample. The distributions of these quantities over the sample periods are compared with corresponding distributions obtained under the hypothesis of random occurrence. It is concluded that the evidence provided by this analysis does not support a hypothesis of significant tidal effects upon earthquake occurrences, in the populations considered.

1. Introduction.

The possibility that tidal forces may "trigger" or otherwise influence earthquake occurrences has received considerable attention in the geophysical literature [ref 1-8]. Unlike the case for moonquakes [6], there is apparent disagreement about whether a relationship between tidal forces (or related phenomena such as ocean tide loading [5]) and earthquake occurrences has been established. It has been suggested [7, 11] that some of the reported negative results (for example, [1]) might be due to making analyses over regions of the earth so large that individual effects related to local mechanisms are masked through averaging or pooling, and hence go undetected.

The present paper reports results of analyses of earthquake occurrences in two relatively small regions along the San Andreas fault in Central California. Region 1 is a rectangle approximately 62 miles long and 18 wide, situated south east of the Calaveras fault junction; Region II is a rectangle 33 miles by 18 miles located just northwest of Region I. Detailed specifications of the regions are given in Table 2. We considered all earthquakes of Richter magnitude 0.0 or greater. 1,732 occurred in Region I and 885 in Region II during the three year period 1 January 1969 to 31 December 1971. These data are from three catalogs by the National Center for Earthquake Research [12].

In order to assist in relating tidal forces to the physical phenomena under study, the forces (and their derivatives, as described below) were expressed as vectors whose components were geometrically related to the fault and presumably the focal mechanisms of the earthquakes occurring in the sample. Since the various components of force do not have a simple distribution over time, and are certainly not uniformly distributed between their minimal and maximal magnitudes, it would be difficult to assess the significance of tidal component magnitudes at times of earthquake occurrences directly. For this reason, we have developed a second, "pseudo earthquake" sample of "events" at random times over the period of study. As described more fully in what follows, comparison of the pseudo sample characteristics with the actual data provides a basis for assessing whether tidal force components have a non random relationship with earthquake occurrences.

2. Analysis Procedure.

The method of analysis is to compare the distributions of components of tidal force and tidal jerk (time rate of change of tidal force) at times of actual earthquakes with corresponding distributions at random times. For the time and location of each earthquake occurrence in our samples, the components of tidal force and jerk shown in Table 1 were computed. Here, the radial direction is oriented outward, perpendicular to the earth's surface (and nearly in the fault plane); the axial direction is northwest, along the fault scarp and the normal direction is perpendicular to the other components (nearly perpendicular to the fault plane). The north-south (N-S) and east-west (E-W) components were in the basis of the coordinate system used in the analyses; the axial and normal were obtained by rotation. The earthquake computations were done using an unpublished computer program which is similar to the one written by Harrison [14]. Samples of 10,000 random times ("simulated earthquake occurrences") were generated over the given time period for the two regions, and tidal force and jerk components were computed at each individual time for the center of the region. An analysis by Corradini [10] shows that the effects of assuming the simulated earthquakes occurred at the centers of such small regions were negligible.

For each component in each region there were thus formed two data samples; a sample of component magnitudes at the times and locations of actual earthquakes and a sample of the same component magnitudes at the simulated, random times. The statistical information contained in each sample can be given in terms of the sample cumulative distribution function (or, simply, "SCDF"). Thus, the SCDF (say F) of a sample $x_1, x_2, \ldots, x_n$ is defined at each real number t by $F(t) = (\text{number } x_i\text{'s less than or equal to } t)/n$. A significant difference in the two SCDF's associated with the two data samples implies that earthquake occurrences are not uniform in time; moreover, this analysis might provide evidence of a tidal effect in earthquake occurrence with respect to the given component. The number of events considered in each region and the length of the periods covered relative to the periods of the tidal components (primarily semidiurnal and diurnal) should "wash out" effects of aftershock sequences in the actual data. Indirect evidence that this assertion is correct is furnished by comparisons of the SCDF's of tidal components for actual and simulated data. If non-uniformity of times of occurrence due to aftershock sequences has an appreciable effect upon the distribution of tidal components at times of actual events, one would expect many if not most of the comparisons of Table 1 to be significant. However, for a great majority of the comparisons made, no significant differences were found. In any case, presence of aftershock sequences should tend to enhance apparent deviations between the actual and simulated samples, so the tests of no difference are conservative. (That is, a conclusion that there is not a significant difference between the observed and simulated samples is made giving "benefit of the doubt" against the conclusion.)

The method used to compare the actual and simulated tidal component distributions was the well-known Kolmogorov-Smirnov (K-S) two sample test [13]. This test is based on the largest (vertical) distance observed between two distributions under comparison, the hypothesis of no difference being rejected when this distance is sufficiently large. We also performed Chi-square tests of the hypothesis of no difference in the actual and simulated distributions. These results are essentially the same as those obtained with K-S procedure, as may be seen in Table 1. The K-S procedure is generally acknowledged to be slightly superior to the χ^2-test in situations like the present, in that the K-S test tends to be more sensitive in detecting differences between two distributions when there is in fact a significant difference [13]. We have included some χ^2-test results here because the latter test is perhaps better known in the scientific community.

As may be seen in Table 1, significance values for regions I and II were not entirely consistent, even though they are adjacent. In order to further investigate the question from a spatial homogeniety, we split each region into two parts along a line parallel to (and nearly coincident with) the fault trace. Specifications of the split are given in Table 2. It was anticipated that differences in the SCDF's associated with the "ocean side" and the "land side" of the fault might provide some evidence for the presence of effects due to ocean loading. In order to examine temporal homogeniety of effects found in the various regions, the period spanned by the data was divided into two parts for each region (see Table 2) and the SCDF's for each subsample were compared. The latter comparisons were made using a two sample Kolmogorov-Smirnov test [13] based on the SCDF's for each pair of samples to be compared. Results are summarized in Table 1.

The analyses described above were also carried out with the earthquake samples modified by omitting all events of Richter magnitude less than 2.0. These results are not reported here, since they were essentially the same as those shown for the full, nontruncated samples.

3. Results.

Table 1 entries give the level of significance of the calculated test statistics for each component of tidal force and jerk. As such, the entries provide a measure of the degree of agreement between the two samples under comparison; a given significance value is the probability of observing as large or larger discrepancy (vertical distance) between the SCDF's, due to statistical chance alone. A value as small as .05 or smaller is often referred to as being "statistically significant," which indicates rejection of a hypothesis of no difference in the populations sampled. However, using $\alpha = .05$ as the threshold for statistical significance, one would expect about 5% of a number of independent tests to reject the hypothesis of no difference, even when in fact the SCDF's are based on samples from identical populations. Thus in analyses such as ours, in which a large number of tests are performed (over a hundred in our case), a few individual significant tests are to be expected. The evidence such tests provide becomes much stronger if replications of the experiment can be run, and they yield the same, or nearly the same, pattern of significance values. In a sense, our analyses of data from the temporally and spatially split regions provided information similar to replications. (We qualify this statement because clearly there is not statistical independence between the entire samples in a region and its "split" sub-samples.) As can be seen in Table 1, there is no apparent consistent pattern of significance values

Table 1. Significance Values for Region I (Region II)

Simulation vs actual

Component	χ^2 test	K-S test	Time Division	Space Di
Normal Tide	.01 (.03)	.20 (.02)	.12 (.76)	.32 (.5
Axial Tide	.06 (.57)	.18 (.44)	.80 (.06)	.24 (.7
Radial Tide	.02 (.97)	.03 (.76)	.90 (.23)	.09 (.8
East/West Tide	.21 (.86)	.16 (.58)	.24 (.38)	.29 (.6
North/South Tide	.24 (.02)	.59 (.006)	.08 (.94)	.12 (.4
Tangential Tide	.34 (.60)	.18 (.12)	.21 (.09)	.001 (.5
Tidal Magnitude	.19 (.04)	.53 (.002)	.10 (.006)	.001 (.2
Normal Jerk	.88 (.54)	.41 (.16)	.99 (.31)	.26 (.2
Axial Jerk	.09 (.26)	.47 (.14)	.14 (.19)	.79 (.6
Radial Jerk	.30 (.55)	.12 (.54)	.18 (.39)	.30 (.6
East/West Jerk	.44 (.17)	.35 (.06)	.38 (.42)	.23 (.4
North/South Jerk	.02 (.71)	.49 (.72)	.45 (.04)	.60 (.2
Tangential Jerk	.83 (.96)	.85 (.49)	.56 (.52)	.07 (.7
Jerk Magnitude	.26 (.53)	.37 (.94)	.48 (.55)	.65 (.5

over the temporal and spacial splits nor between the adjacent regions. Admitted the rate of significance appears to be high: among the K-S tests, 9 significant out of 84 tests, a sample rate of 11%. If the underlying tests were independen this would in itself be significant ($P \approx .01$). However, these tests are <u>not</u> independent, even within a given sub-region. For example, the normal and axial components are obtained by rotation from the N-S and E-W components, and hence can be expected to be correlated. Similarly, geometric and mathematical relationships among other of the components lead to lack of independence. This fact makes it very difficult to statistically assess the true significance of the number of significant tests we found in our analysis. Overall, we are inclined to conclude that there is little evidence here to support a hypothesis of significant tidal effects upon earthquake occurrences, in the populations we sampled.

Table 2

Region I - Coordinates: (121.50W, 36.70N), (120.80W, 36.00N), (120.60W, 36.20N), (121.50W, 36.90N).

	Coordinates*	Time †	Sample sizes§
Simulation 10000		Jan. 1, 1969 thru Dec. 31, 1971	1732** (378)††
Space div.	(121.41W, 36.79N) (120.71W, 36.09N)	Same as above	699, 1033 (181), (197)
Time div.		Split at July 1, 1970	565, 1166 (145), (232)

Region II - Coordinates: (121.97W, 36.98N), (121.55W, 36.63N), (121.35W, 36.83N), (121.78W, 37.17N).

	Coordinates	Time	Sample sizes
Simulation 10000		Jan. 1, 1969 thru Dec. 31, 1971	885 (144)
Space div.	(121.87W, 37.07N) (121.45W, 36.73N)	Same as above	70, 813 (26), (118)
Time div.		Split at July 1, 1970	435, 449 (67), (76)

*end point coordinates of division line.

†the entries for temporal divisions are division points within the time period under consideration.

§for split regions, the first number is sample size for the "ocean", i.e., southwest side and the second is a sample size for the "land" side; in the case of temporal divisions, sample size for the earlier period is given first.

**all magnitudes, full sample

††sample sizes for sample truncated at $M = 2.0R$ in parentheses

In order to provide an appreciation of the size of difference between the SCDF's associated with a significant K-S test, we show in Figure 1 a plot of the SCDF's for the Radial Tide Component in Region I. The maximal vertical distance between these plots is only about .03; with the sample sizes involved (10,000 simulated events and 1732 actual events) this was significant with $P \approx .03$ as shown in Table 1.

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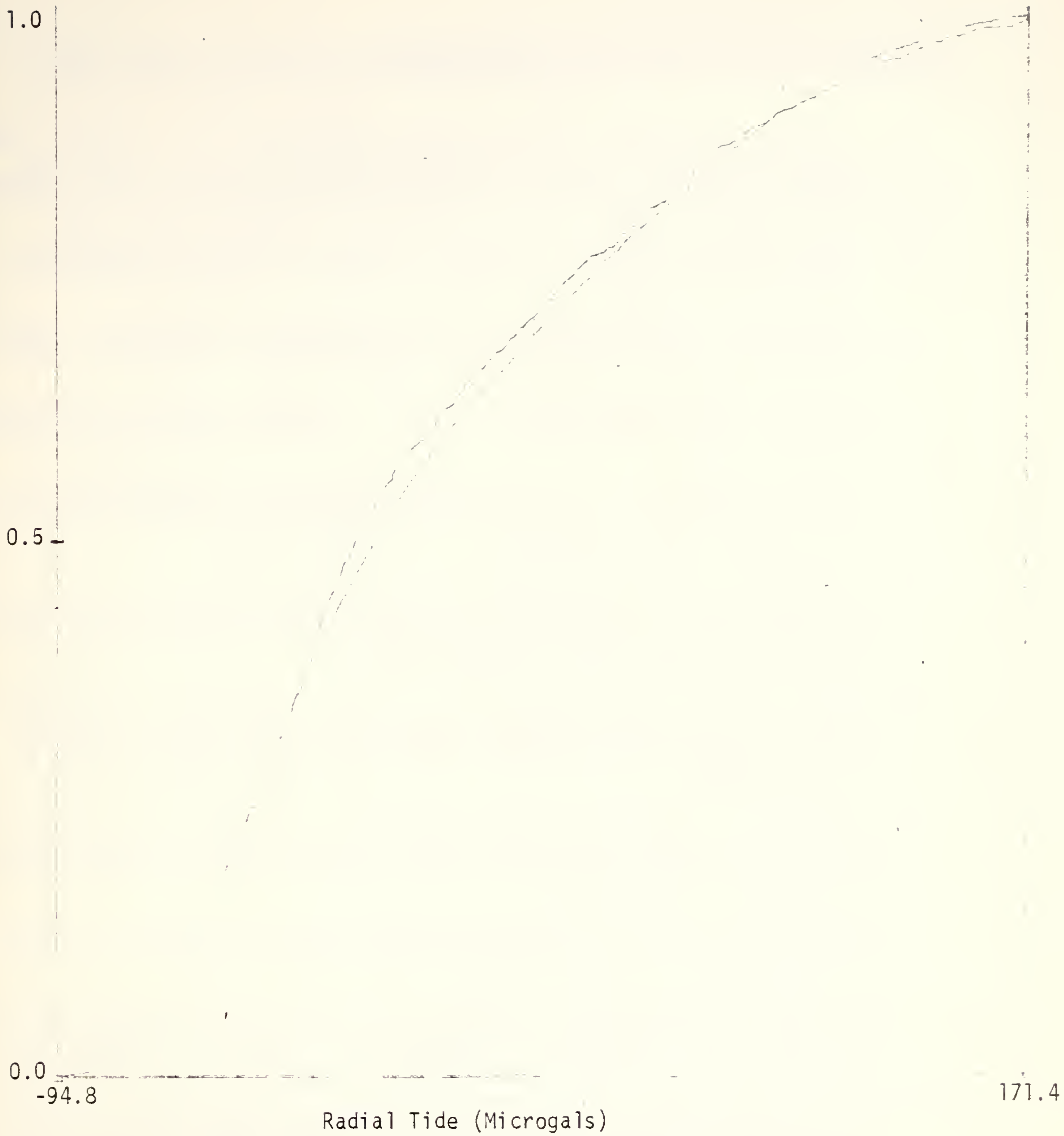

Figure 1. Plots of radial tide SCDF's for the sample of actual events and the simulated sample. The curve corresponding to the simulated sample is smoother than the other, due to the larger sample size involved.

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